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# Pattern of southern Laurentide Ice Sheet margin position changes during Heinrich Stadials 2 and 1

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ABSTRACT

With concerns over rising global temperatures, ice sheet stability and implications for sea level rise, the responses of former ice sheets to past climate change provide useful insights into linkages between the atmosphere, cryosphere and oceans. One example is the behavior of the Laurentide Ice Sheet (LIS) during Heinrich Stadials, times of cooler sea surface temperature (SST) in the North Atlantic. Using existing cosmogenic surface exposure ages, varve chronologies, radiocarbon ages, and optically stimulated luminescence ages from the southern LIS margin, this report tests the hypothesis that the southern side of the LIS advanced during times of surface cooling of the North Atlantic. This test reconstructs the timing of local glacial maxima and the times immediately pro- and preceding them, from multiple areas and compares them to the timing of Heinrich Stadial 2 (HS2; 26.6–23.6 ka) and to the timing of Heinrich Stadial 1 (HS1; 19.3–15.3 ka).

During HS2 southern sector lobes (New England region, Huron-Erie Lobe, Lake Michigan Lobe, Green Bay Lobe and the Chippewa Lobe) advanced towards their maximum position, except for the Des Moines Lobe for which there is no applicable data. During HS1 these same lobes experienced substantial retreat, but the Des Moines Lobe advanced. Thus, the southern Laurentide margin behaved differently during the two Heinrich Stadials. This pattern may be attributed to differing east-west temperature gradients across North America and associated changes in atmospheric circulation.

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## 1. Introduction

The connections between ice sheets and ocean systems remain incompletely understood. A specific example of this problem is the relationship between the North Atlantic Ocean and the Laurentide Ice Sheet during the late Pleistocene. Did the terrestrial margin of the southern Laurentide Ice Sheet advance during cold phases of sea surface temperature (SST) in the adjacent North Atlantic? This question has yet to be explored in the context of millennial-scale sea surface temperatures (SST) changes, although it bears on the possibility of direct linkages between ice-sheet and ocean systems. Here the timing of the two most recent intervals of cold SST in the North Atlantic, known as Heinrich Stadials (HS) 2 and 1 is compared to the advance and retreat history of the southern Laurentide Ice Sheet (LIS).

Heinrich Stadials refer to the periods of cool sea surface temperatures during which Heinrich Events occur (Bond et al., 1992; Bond and Lotti, 1995; Bard et al., 2000). Heinrich Stadials are detected in marine sediment cores records as changes in planktonic foraminifera assemblages, Mg/Ca ratios or $U^{K}_{37}$ alkenones (Waelbroeck et al., 2001; Naughton et al., 2009; Salgueiro et al., 2014; Schönfeld et al., 2003; de Abreu et al., 2003; Voelker et al., 2009; Bard et al., 2000; Chapman et al., 2000). To date, six distinct Heinrich Stadials have been identified in the last 100,000 years, and they are numbered sequentially from youngest to oldest (1–6). Heinrich Stadials are different than “Heinrich Events”, which are sediment layers rich in ice-rafted debris in North Atlantic marine sediment cores first described by Heinrich (1988). Heinrich Event layers are interpreted to result from massive iceberg discharges from the Laurentide Ice Sheet (e.g. Hemming, 2004, Hodell et al., 2017). There is an important difference between the terms Heinrich Event and Heinrich Stadial. Rather than a specific event, Heinrich Stadials are 1–2 kyr spans of persistently cold North

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Atlantic SST.

The Laurentide Ice Sheet was the largest ice sheet of the last glacial period (Denton and Hughes, 1981) and covered much of North America (Fig. 1). Its southern margin spanned nearly 3000 km across the central continent and culminated in multiple distinct lobes (Flint et al., 1959; Mickelson and Colgan, 2003).

## 2. Data and methods

### 2.1. Establishment of Heinrich Stadial timing

This study is focused on the two youngest Heinrich Stadials 2 and 1 (HS2 and HS1) for two reasons. First, they are the best dated of the Heinrich Stadials, and second, they correspond to time intervals with the richest data set and the best preservation of morphological evidence of ice-sheet behavior. Here the term "stadial" refers to a time of relatively cold SST in the North Atlantic, and the term "interstadial" refers to a time of relatively warm SST in the North Atlantic. Bard et al. (2000) reconstructed the SST conditions around the time of Heinrich events using $U^{K}_{37}$ alkenones for a sediment core off the Iberian Peninsula. They reported a 2–3 °C decrease in SST at minimum, at several locations in the North Atlantic during both Heinrich Stadials 2 and 1. Subsequent studies of North Atlantic marine sediment cores have confirmed this cooling during Heinrich Stadial times (e.g. Rasmussen et al., 2003; Hodell et al., 2017), and additional studies (e.g. McManus et al., 2004; Bradtmiller et al., 2014) suggest reduced meridional overturning in the North Atlantic during Heinrich Stadials.

For this purpose of this study, the timing of Heinrich Stadials was established using dated marine cores (Fig. 2; Table 1). The motivation behind this method was to develop an independent age range for the stadials using only SST proxies. Marine sediment cores from the North Atlantic that were selected for this study each have an independent $^{14}C$-based age model, which have not been tuned to ice core records or other sediment cores. In addition, each core record yields a sea surface temperature record derived from one or more of the three following proxies: $U^{K}_{37}$ alkenones, planktonic foraminifera assemblages and Mg/Ca ratios.

The goal here is to make a direct chronological comparison between a proposed forcer of SST and resulting response of ice margin changes on a common time scale. Therefore, the radiocarbon chronology associated with each individual sediment core was recalibrated using the IntCAL13 dataset (Reimer et al., 2013) and the age-depth model for each core was reconstructed using data from the original sources. The start and end timing for Heinrich Stadials 2 and 1 were determined using the original core records and compared to the newly calibrated age model for each core. These start and end depths and times are compiled in Table 1.

Since the age ranges for each Heinrich Stadial varied between the individual studies, the most probable age range of the existing data was determined using the following method. Using a 10-year bin from 30.0 to 14.0 ka, a "1" was assigned for each bin if the reported age range from each marine core fell within a Heinrich Stadial, or "0" otherwise. The occurrences for each bin were then summed and the relative probability was computed with the area under the resulting histogram equal to one. The results (Fig. 2) are plotted numerically as area under the curve and visually as a relative gray scale. The start and end time for each stadial was determined at both the 68% (1-sigma) and the 95% (2-sigma) confidence levels (Table 1). For the purposes of this study, the latter is used in both cases. Heinrich Stadial 2 is reflected as two "peaks" or "phases" (Table 1) in the probability analysis, however due to the uneven distribution as reflected in Fig. 2, these have been combined as one phase. This analysis indicates cold phases HS2 (26.6–23.6 ka) and HS1 (19.3–15.3 ka) punctuated by a period of warmer sea surface temperature in the North Atlantic, termed here the Heinrich Interstadial (HI; 23.6–19.3 ka). We return to this point in the discussion.

### 2.2. Chronologic data of Laurentide Ice Sheet history

The ice margin position of the southern Laurentide Ice Sheet

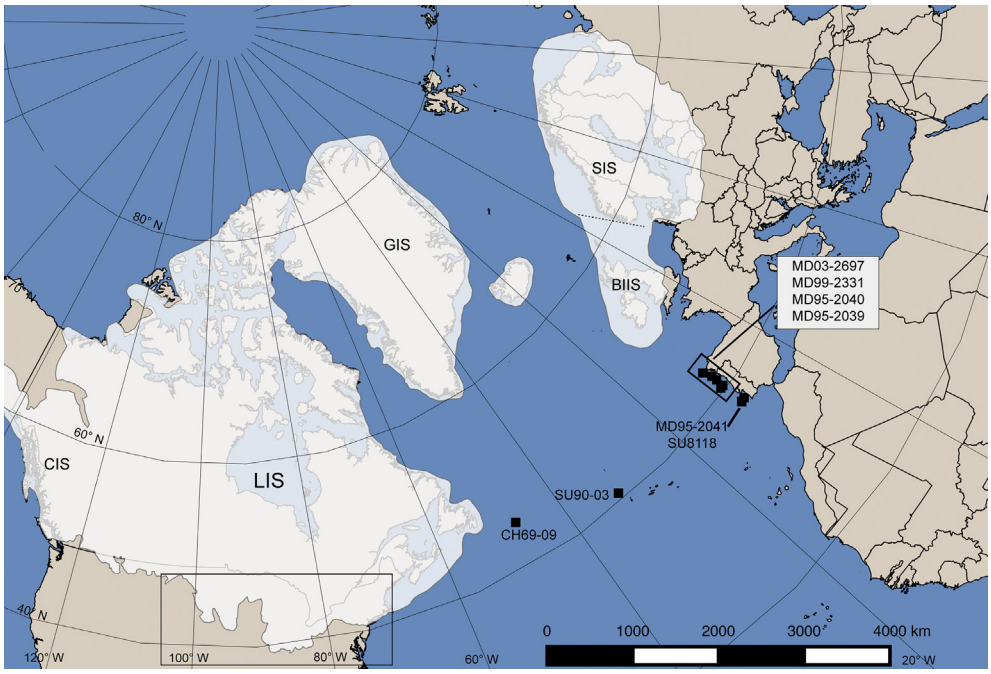


**Fig. 1.** Map of the Northern Hemisphere ice sheets during the last glacial period (LIS = Laurentide Ice Sheet, GIS = Greenland Ice Sheet, CIS = Cordilleran Ice Sheet, BIIS = British-Irish Ice Sheet, SIS = Scandinavian Ice Sheet). Black squares represent locations of North Atlantic marine cores used in reconstructing Heinrich Stadial timing (Table 1). Box over central North America represents area detailed in Fig. 3. Modified from Dyke (2004).

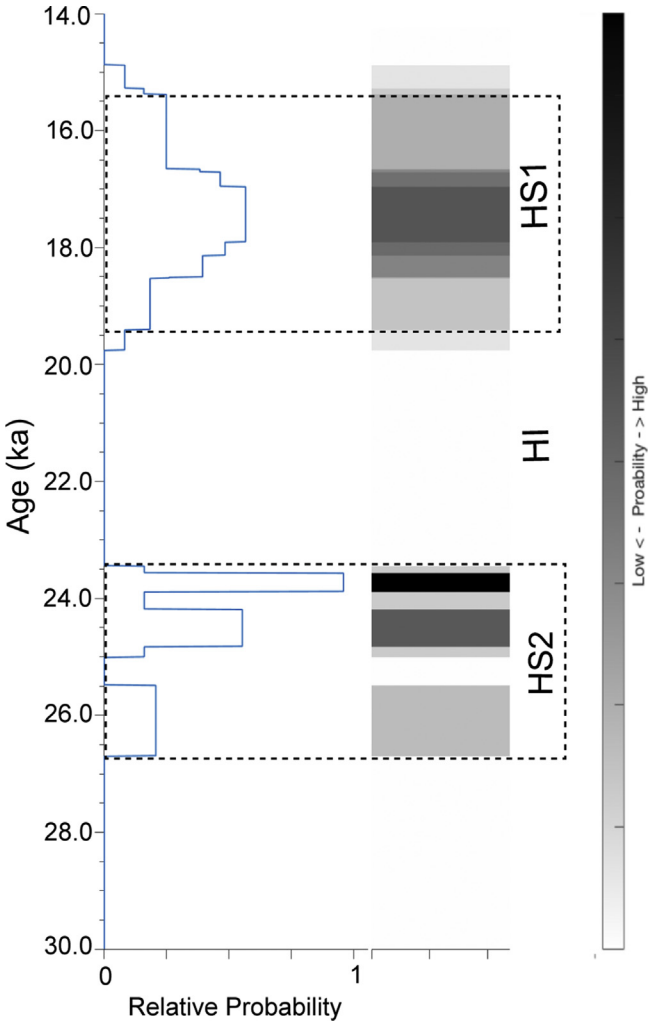


**Fig. 2.** Analysis of Heinrich Stadial timing based on results from SST records compiled in Table 1. The first graph on the left is the relative probability of a given time slice being included in Heinrich Stadials 2 or 1. This probability is represented in shades of gray on the right. Dashed boxes outline the interpreted age range for HS2 (26.5 to 23.5 ka) and HS1 (17.5–15.5 ka). Heinrich Interstadial (HI) is also indicated from 23.5 to 17.5.5 ka.

over time is tracked by stratigraphic correlations and geomorphological and sedimentological features (moraines, till, outwash, etc.). Many of these features have been assigned ages using cosmogenic exposure, varve counting, or radiocarbon dating techniques. The reported context of the geomorphic features and varves, as well as sedimentological and stratigraphic relationships were used to determine if the ice sheet was advancing or retreating and then use the chronology to assign an age for that behavior. The maximum extent of the LIS during the last glacial period has been mapped extensively in most places, most notably by Flint et al. (1959), and in subsequent US Geological Survey 4 × 6°, 1:1,000,000 scale quadrangles (Goebel et al., 1983; Lineback et al., 1983; Farrand et al., 1984; Dyke and Prest, 1987; Fullerton et al., 1991; Gray et al., 1991; Hallberg et al. 1991; Hartshorn et al., 1991; Howard et al., 1991; Fullerton et al. 1991, 1992; Whitfield et al., 1994). Most stratigraphic and chronologic data comes from near the maximum limit of the ice sheet. Therefore, the focus was on all chronologic data with known stratigraphic context (sediment unit or feature) within ~200 km of the outermost moraine for each of the six individual lobes (Fig. 3). Any changes in ice margin position would be reflected in the outermost 200 km of each lobe. This paper deals with changes in the ice sheet specifically during Heinrich Stadials 2 and 1, therefore only chronologic control between 28.0 and 15.0 ka was considered. This review includes all known age analyses in the literature relevant to this question. Limited unpublished data from the authors is also included here.

The following is a brief description of each dating method and individual calibration method as well as the interpretation strategy.

Cosmogenic radionuclide exposure ages represent the amount of time since the boulder sampled was uncovered by ice and exposed to cosmic rays, and is taken here as a minimum age for the formation and stabilization of the moraine. All surface exposure ages here were calculated using the CRONUS-Earth online exposure age calculator version 2.2 (Balco et al., 2008), using the north-eastern North American production rate developed by Balco et al. (2009), and the scaling scheme described by Stone (2000) following Lal (1991). The erosion rates and sample densities input came from the original literature source (Table S1). Sample details and analytical results, as well as estimated ages, are provided in Table S1.

Varves are distinct layers of sediment that record variations in seasonal melt water input. Varves occur as seasonal couplets with summer varves that can vary in thickness due to proximity to the ice margin position; the closer to the ice margin, the thicker the varve. These varve sequences, if present in multiple sediment cores, such as along the Connecticut River Valley in New England (Ridge et al., 2012), can be correlated using stratigraphy as well as radiocarbon ages of organics within the sediment. Ridge et al. (2012) used organic materials within the varves to assign the Connecticut River Valley varve records an absolute age. This sequence tracks the New England region ice sheet margin.

Radiocarbon ages represent the amount of time that has passed since the dated organic material was alive. Thus, they offer either maximum or minimum constraints on changes in glacier margin position. A radiocarbon age of material from within or below a glacial till provides a maximum age for advance, because the age represents organic material living before being incorporated by advancing ice or buried by proglacial deposits. Radiocarbon ages of organic material found in outwash deposits, kettle lakes, ice-walled lake plains and other basins are interpreted as minimum ages for glacial advance. Only radiocarbon ages with certain stratigraphic context were considered in this study. All $^{14}C$ ages were recalibrated using CALIB 7.1 software, with the IntCal13 calibration curve (Reimer et al., 2013). Radiocarbon ages are presented in the text and figures as the mean calibrated age (abbreviated as ka, thousands of years before 1950). The radiocarbon ages utilized here are presented in Supplementary Table S2.

Optically stimulated luminescence (OSL) ages represent the time elapsed since sediment was buried and no longer exposed to light. In this study, these ages come from proglacial-lake sediments. These must be considered in context as outwash can reflect both advance and retreat of the ice sheet edge. Analysis results and sample information for all OSL ages are compiled in Table S3. In total, this study utilizes 82 $^{10}Be$ surface exposure ages, 6 varve-derived ice margin positions, 430 radiocarbon ages, and 9 OSL ages to reconstruct the behavior of the ice sheet.

### 2.3. Analysis

For each lobe, a time-versus-distance plot for each lobe is constructed to represent the advance and retreat pattern. Each chart features individual ages plotted along a flow line drawn parallel to the long axis of each lobe. The stratigraphic context of each sample was considered (maximum versus minimum age for ice sheet position) in order to “track” each lobe's position over time. An

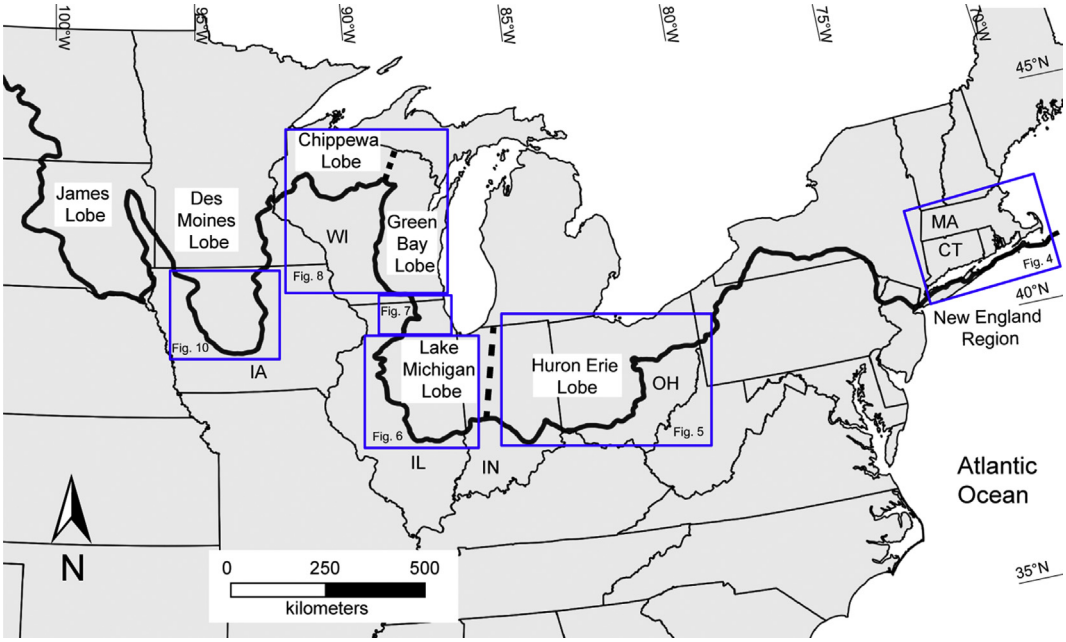


**Fig. 3. Map of Southern Laurentide Ice Sheet margin**. Lobes of the southern Laurentide Ice Sheet. The bold black line represents the outermost moraine of each lobe (after Flint et al., 1959, Mickelson and Colgan, 2003). Dashed black lines represent the approximate boundaries between Lake Michigan Lobe/Huron Erie Lobes and Chippewa/Green Bay Lobes. Solid blue boxes indicate locations of following figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
**Heinrich Stadial Timing Raw Data**. Compilation of marine sediment cores and proxies used to determine timing of Heinrich Stadials 2 and 1. The core ID, location and reference are provided. The start and end depth columns refer to the core depths at which temperature change was interpreted as transitions in and out of Heinrich Stadials 2 and 1. These depths were used to determine stadial timing. [1]Event not detected in SST record.

| Core ID | Latitude (°) | Longitide (°) | SST Metric | Heinrich Stadial 2 | | | | | | | | Heinrich Stadial 1 | | | | Reference(s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Phase 1 Start Depth (m) | Phase 1 End Depth (m) | Phase 1 Start Age (ka) | Phase 1 End Age (ka) | Phase 2 Start Depth (m) | Phase 2 End Depth (m) | Phase 2 Start Age (ka) | Phase 2 End Age (ka) | Start Depth (m) | End Depth (m) | Start Age (ka) | End Age (ka) | |
| CH 69-09 | 45.00 | −47.35 | Plank. Foram. | | | | | ND[1] | | | | 3.1 | 2.85 | 19.4 | 17.0 | Waelbroeck et al., 2001 |
| MD03-2697, MD99-2331 | 42.16 | −9.7 | Plank. Foram. | 6.95 | 6.6 | 28.0 | 27.0 | 6.5 | 6.1 | 26.7 | 25.8 | 2.5 | 2.0 | 18.5 | 16.7 | Naughton et al., 2009, Salgueiro et al., 2014 |
| MD95-2039 | 40.58 | −10.35 | Plank. Foram. | 6.3 | 5.8 | 26.7 | 25.5 | 5.6 | 5.0 | 25.0 | 23.5 | 3.1 | 1.8 | 18.5 | 15.3 | Schönfeld et al., 2003 |
| MD95-2040 | 40.58 | −9.86 | Plank. Foram. | | | | | ND[1] | | | | 3.1 | 2.1 | 18.1 | 15.4 | de Abreu et al., 2003 |
| MD95-2041 | 37.83 | −9.52 | Plank. Foram. | 4.7 | 4.5 | 24.8 | 24.2 | 4.4 | 4.3 | 23.9 | 23.6 | | ND[1] | | | Voelker et al., 2009 |
| SU8118 | 37.7667 | −10.1833 | $U^{K}_{37}$ | | | | | ND[1] | | | | 3.3 | 2.5 | 17.9 | 14.9 | Bard et al., 2000 |
| SU90-03 | 42.16 | −9.7 | Plank. Foram. | | | | | ND[1] | | | | 0.9 | 0.75 | 19.8 | 16.7 | Chapman et al., 2000 |

interpretation of whether the lobe was advancing, retreating or if the behavior is unknown is included in the discussion section.

## 3. Results of chronologic data compilation

### 3.1. New England Region

The ice sheet margin in the New England Region reached as far south as 41°N, a position marked by a distinct moraine at present-day Long Island, Martha's Vineyard and Cape Cod (Fig. 3). Sirkin and Stuckenrath (1980) report maximum radiocarbon ages for organic material collected from within and below till exposed at sites near the New England region, such as the Harbor Hill moraine on Long Island. Some of these ages fall numerically within HS2, however due to multiple age reversals within the stratigraphy, these ages have been excluded from this analysis.

In southeastern Massachusetts, three $^{10}$Be exposure ages of $26.3 \pm 1.0$, $25.5 \pm 0.7$, and $24.9 \pm 0.7$ ka come from boulders collected from the terminal moraine at Martha's Vineyard (Site 1; Table S2; Balco et al., 2002). Consistent with the original authors (Balco et al., 2002), two outliers with relatively young ages of $22.8 \pm 0.9$ ka and $17.8 \pm 0.7$ ka were excluded. Four samples with exposure ages greater than 28.0 ka were excluded for this analysis because they fall outside the age range criteria outlined in the methods above. The three ages from Site 1 provide an average age of $25.5 \pm 0.4$ ka for the timing of moraine abandonment following

the ice margin's most extensive advance in New England. This scenario requires that the ice sheet was advancing before this time. Balco et al. (2002) also present ten $^{10}$Be exposure ages from the Buzzards Bay recessional moraine on Cape Cod, MA (Site 2), which lies about 15 km north of the terminal moraine, that range from 22.8 ± 0.8 to 19.1 ± 0.8 ka with an average of 21.3 ± 0.4 ka (Balco et al., 2002). Balco and Schaefer (2006) present fourteen $^{10}$Be ages from boulders atop recessional moraines in southern Connecticut, which range from 21.8 ± 0.7 to 19.7 ± 0.5 ka (Ledyard Moraine, Site 3) and 22.2 ± 0.6 to 19.9 ± 0.5 ka (Old Saybrook moraine, Site 4; Fig. 4a; Balco and Schaefer, 2006, Balco et al., 2009). The average age for these two sites are 20.7 ± 0.3 ka and 21.1 ± 0.4 ka, respectively. Taken together, these ages suggest that advance of the Laurentide ice margin in the New England region occurred before 25.5 ± 0.4 ka, which is derived from the age of the Martha's Vineyard moraine, which is the outboard location of the LIS local maximum in this region. The Buzzards Bay moraine was uncovered ~21.3 ± 0.4 ka, which suggests that retreat was underway by that time. Retreat continued over the next several thousands of years, uncovering the Ledyard and Old Saybrook moraines in southern Connecticut by ~20.7 ± 0.3 ka.

The present framework for New England's subsequent deglacial history is based on the varve records presented by Ridge et al. (2012). This record is compiled from sediment outcrops and cores across the Connecticut River Valley and the age model is based on radiocarbon ages from these cores and supported by surface exposure ages discussed above. Between ~18.6 ± 0.2 and 17.3 ± 0.2 ka, the margin underwent retreat from its position at the Ledyard and Old Saybrook moraines in southern Connecticut (Ridge et al., 2012; J. Ridge, personal communication). The pattern of retreat was interrupted by two minor readvances, the first being a ~30 km readvance ~17.3 ± 0.2 ka in southern Massachusetts (named the Chicopee Readvance). Ridge et al. (2012) also acknowledge a second readvance of unknown magnitude ~16.0 ± 0.2 ka in northern Massachusetts, termed the Hatfield Readvance.

In summary, the ice margin of the New England region advanced during the entirety of HS2 (Fig. 4b). The ice remained near its maximum position until ~23 ka and continued retreating during HS1, with the exception of two minor readvances ~17.3 and ~16.0 ka (Fig. 4b).

### 3.2. Finger Lakes region

Early work on the timing of glaciation in New York (Muller and Calkin, 1993) concluded that the maximum extent was reached between ~21.8 and ~18.6 ka, which is based on morphostratigraphy and correlation with nearby moraine systems. Recent work in the Finger Lakes region of New York, ~150 km north of the terminal moraine, yield minimum ages for retreat of the margin (Kozlowski et al., 2018). These sites lie just north of the Outer Valley Heads moraine, which is interpreted as the product of a readvance ~17.0 ka (Muller and Calkin, 1993). These new minimum ages range from 15.0 ± 0.1 to 13.7 ± 0.1 ka, and suggest that the margin had retreated more than 150 km from its terminal position by ~15.0 ka. This is consistent with the history of the New England region to the east. Although these ages fall strictly outside of our criteria, they can be taken to suggest ice sheet retreat in this sector during HS1.

### 3.3. Lake Huron-Erie Lobe

The Lake Huron-Erie Lobe advanced southward across Ohio from the Lake Huron and Erie basins and reached its southernmost extent at ~39° latitude, in southwestern Ohio (Fig. 2). The lobe also extended westward into eastern Indiana and eastward into northeastern Ohio, northeastern Ohio (Figs. 3 and 5). The maximum timing for advance is constrained using radiocarbon ages of organics recovered both from within or beneath the glacial till.

Maximum radiocarbon ages for the initial advance of the Lake Huron Erie Lobe are from the Garfield Heights site in northeastern Ohio (Fullerton, 1986; Sumodi, 1974), which range from 28.9 ± 1.5 to 26.4 ± 0.3 ka (Fig. 5a, Site 26). Five radiocarbon ages from the Sidney RR Cut (Site 64; Forsyth, 1965, Lowell et al., 2018) that range from 27.7 ± 0.2 and 26.9 ± 0.3 ka are consistent with those from the Garfield Heights site. These ages imply that advance was underway prior to the start of HS2 (Fig. 5b). The ice margin advanced over the Oxford, OH area, where seven radiocarbon ages of wood from the lowermost till exposed at the Oxford East site (Site 71a) range from 26.6 ± 0.7 to 24.7 ± 0.6 ka, which are maximum ages for the ice margin advance. This till is overlain by a distinct gastropod-rich silt unit, which is exposed at several sites including Oxford East (Site 71b) in Ohio. The presence of this silt unit, as well as the gastropods within, indicate a retreat of the ice margin and suggests temporarily warmer conditions. Radiocarbon ages from this unit provide a minimum bracketing age for this retreat, and a maximum age for the overlying till and associated advance. At Oxford East (Site 71b), ages range from 25.7 ± 1.4 to 24.2 ± 1.3 ka (Pigati et al., 2010). New radiocarbon ages from the silt layer underlying till, as observed in a sediment core from the Brush Creek Site in Indiana (Site 45), range from 24.8 ± 0.4 to 23.9 ± 0.3 ka. Based on stratigraphic correlation as well as the radiocarbon ages, the interstadial silt and upper till were both deposited during the second phase of HS2.

Radiocarbon ages of wood from till that occur stratigraphically higher than the Oxford East silt unit provide minimum ages for the end of this brief interstadial, and also provide maximum age constraint for a second advance. A till unit exposed at the Oxford West site (Site 70) and Oxford Middle site (Site 69) overlies the gastropod-rich interstadial silt and contains organics with radiocarbon ages that range from 25.7 ± 0.4 to 23.6 ± 1.5 ka (Ogden and Hay, 1973; Suess, 1954; Ekberg et al., 1993; Lowell and Brockman, 1994). Consistent with these ages are seven ages from Milford Cemetery (Site 72) that range from 24.5 ± 0.5 to 22.5 ± 0.2 ka, and three ages from Doty's Highbank (Site 67) which range from 26.5 ± 0.5 to 24.7 ± 0.4 ka. Finally, seven radiocarbon ages from logs broken by the ice during an advance, recovered by the nearby Reily Site range from 27.3 ± 0.4 to 22.7 ± 0.3 ka (Site 73; Ekberg et al., 1993, Lowell and Brockman, 1994).

Lowell et al. (1999) summarize radiocarbon ages from four sites near Cincinnati, Ohio (Sites 68, 75–78; Fig. 5b), which are interpreted as maximum ages for a second HS2-age advance based on their stratigraphic position (Goldthwait, 1958; Lowell et al. 1990, 1999; Lowell and Brockman, 1994). These thirty-one ages range from 26.8 ± 0.6 to 23.1 ± 0.4 ka and are from wood either within or below the till unit at each site. Younger ages from south central Ohio come from the Chillicothe sites (Sites 38, 39, 40), which range from 22.7 ± 0.7 to 21.2 ± 0.6 ka (Goldthwait, 1958; Ogden and Hay, 1964; Goldthwait et al., 1981; Lowell et al., 1999). Similar radiocarbon ages from the nearby Hamilton (Site 74) range from 23.8 ± 0.7 to 22.6 ± 0.7 ka (Rubin and Alexander, 1960; Olson and Broecker, 1961). The Snyder Farm site in Indiana (Site 66) also lies just within the late Wisconsin limit. Radiocarbon ages of wood collected there range from 24.5 ± 0.6 to 22.0 ± 0.5 ka (Gooding, 1963; Hall et al., 1992; Hall and Anderson, 2000). Taken together, the chronology of the western Huron-Erie Lobe suggests two advances during HS2, separated by a minor retreat and interstadial conditions.

Glover et al. (2011) present a comprehensive deglacial chronology for Ohio and Indiana, which includes 29 previously unpublished radiocarbon ages from post-glacial organic sediments deposited following retreat of the four sublobes of the Huron-Erie Lobe across eastern Indiana and central and western Ohio (Fig. 5).

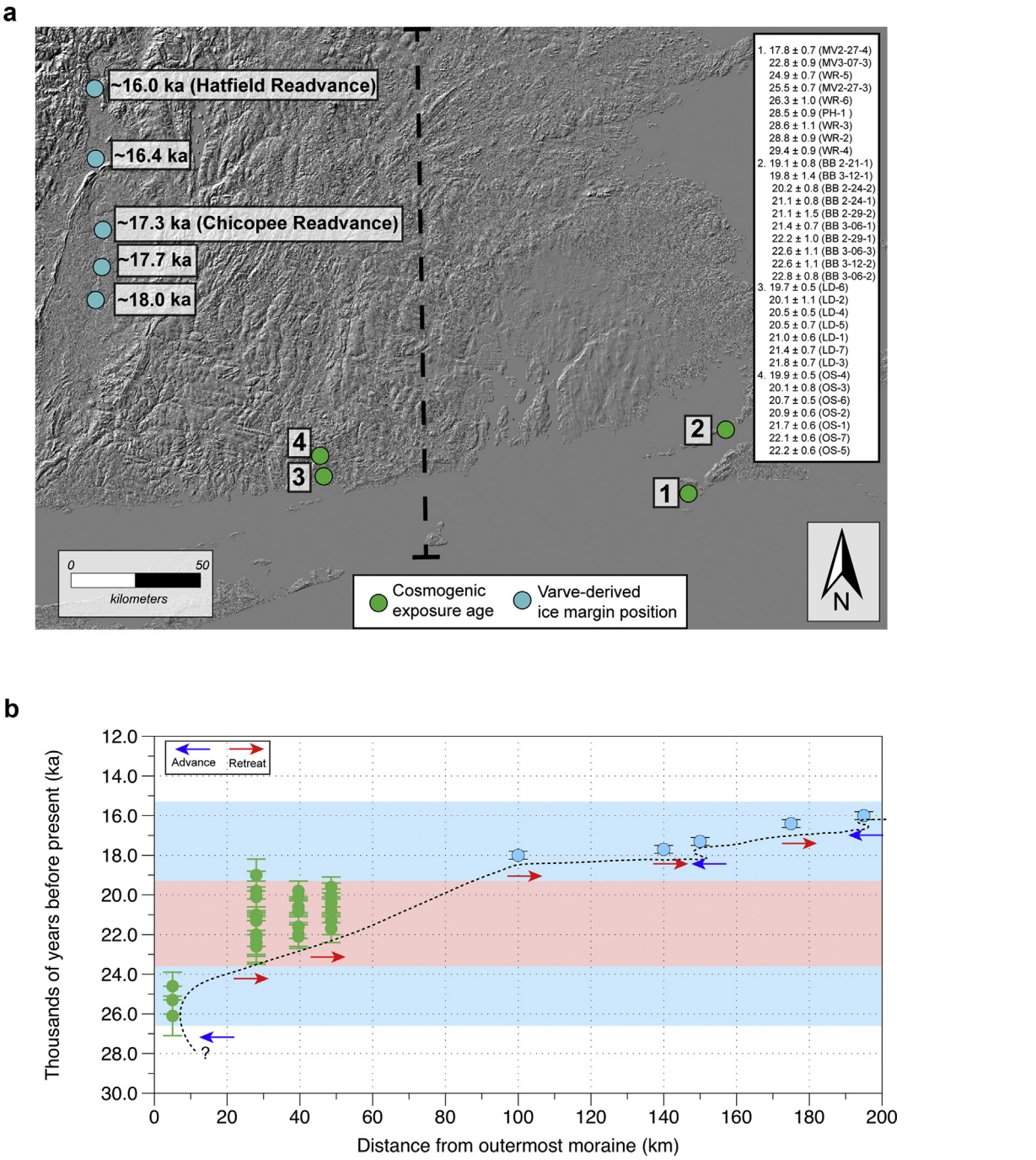


**Fig. 4. New England Margin Chronologic Data.** a) Map featuring a digital elevation model (DEM) of the New England region in Massachusetts and Connecticut. The DEM was generated from NASA's Shuttle Radar Topography Mission (SRTM), with a sampling of 3 arc-seconds or 90 m. Ages are reported in thousands of years before present (ka) and correspond to sites pictured on map and presented in Supplementary Table 1S b) Time/distance plot of the New England region using data presented on map. Transect line for ice margin position interpretation is the dotted line. Blue bars represent Heinrich Stadials 2 and 1, while red bar represents the intervening warmer period here called Heinrich Interstadial. HS2 has been divided to provide visual representation of possible warming during period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Taken together, the chronology of Glover et al. (2011) as well as previously published radiocarbon ages from post-glacial sediments provide a minimum constraint for retreat and range from 19.8 ± 0.4 to 14.2 ± 0.7 ka (Ogden and Hay, 1965; Ogden and Hay, 1967; Mills, 1975; Totten, 1976; Hood et al., 1983; Richards et al., 1987; Shane, 1987; Shane, 1989; Lepper et al., 1991; Shane and Anderson, 1993; Frolking and Szabo, 1998; Tankersley, 1999; Wiles et al., 2002; Pritchard, 2006; Lutz et al., 2007; Gill et al., 2012). Retreat was underway in some parts of Ohio before 19.8 ± 0.4 ka, during early HI (23.5–17.5 ka). This is based on the oldest ages which come from Mechanicsburg (Sites 15, 16), Murphy's Bog (Site 13), Farm Pond (Site 12).

### 3.4. Lake Michigan Lobe

The Lake Michigan Lobe flowed through the present Lake

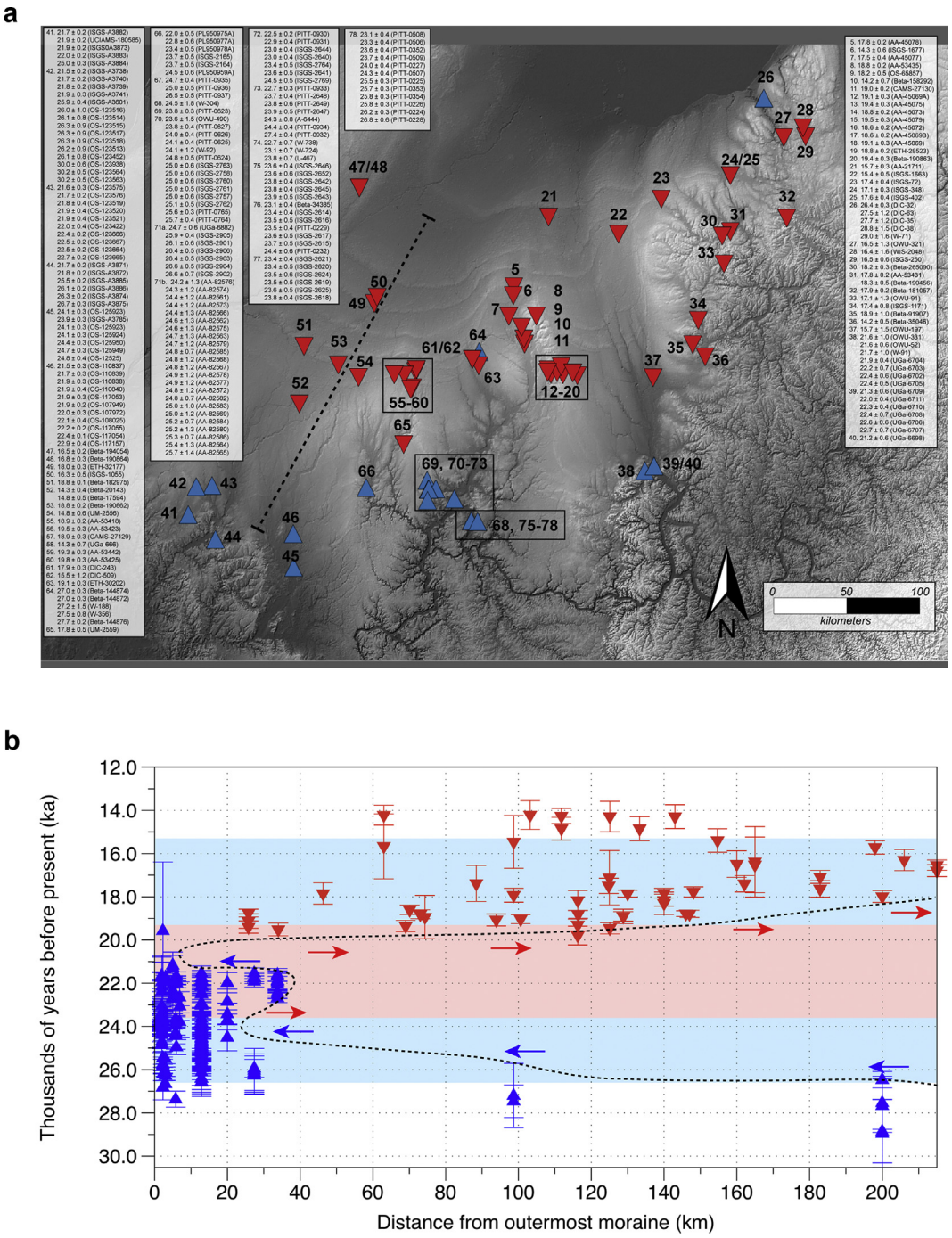


**Fig. 5. Lake Huron-Erie Lobe Chronologic Data** a) Map featuring radiocarbon ages of the Lake Huron-Erie Lobe in Ohio and Indiana. Ages are reported in calibrated years before present (ka). Upright blue triangles represent maximum radiocarbon ages, while downward-pointing red triangles represent minimum radiocarbon ages. b) Time/distance plot with Huron-Erie Lobe ice margin position interpretation superimposed as a dotted line. Blue bars represent Heinrich Stadials 2 and 1 cold periods, and red shaded horizontal bar represents Heinrich Interstadial warm period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Michigan basin to its terminal position in central Illinois (Fig. 2). The lobe also fed the Harvard Sublobe to the north, which flowed westward from the Lake Michigan Basin into northern Illinois and southern Wisconsin. Minimum and maximum radiocarbon ages of organics constrain the timing of advance and retreat during the Heinrich Stadials and HI. To track the glacier margin only, we exclude radiocarbon ages from intermediate till, loess, glaciolacustrine, and outwash units in the Lake Michigan Lobe. This means radiocarbon ages from three units were used here - ages from two loess units that underlie the entire sequence as maximums for advance, and the ice-walled lake plain deposits at the surface as minimums for retreat.

### 3.4.1. Lake Michigan Lobe chronology

The Robein Member of the Roxana Silt and the Morton Tongue of the Peoria Silt directly underlie the Wedron Group of glacial tills. Therefore, radiocarbon ages of organics from these units provide a maximum constraint for advance. Sites located near the outer

moraine belts of the Lake Michigan Lobe in central Illinois (Sites 102–108, 110–112, 114–123, 125, 126, 129; Fig. 6) yield 37 radiocarbon ages that range from 29.0 ± 1.9 to 23.3 ± 0.5 ka (Rubin and Alexander, 1958; Kim, 1970; Kempton and Gross, 1971; Johnson et al., 1971; Coleman, 1973; Liu and Coleman, 1981; Liu et al., 1986; Johnson and Hansel, 1990; Hansel and Johnson, 1996; Grimley et al., 2016), with one anomalously young age of 21.7 ± 0.5 ka (Site 118; this study). These ages provide a maximum constraint for advance of the Lake Michigan Lobe into south central Illinois. Ages from the same silt units exposed in northeastern Illinois (Sites 91, 93, 95, 101 and 113) range from 29.0 ± 0.5 to 27.2 ± 2.0 ka (Kempton et al., 1968; Hansel and Johnson, 1996; Johnson and Hansel, 1990; Curry et al., 1999; Curry, 2015).

Two noteworthy readvance events in Lake Michigan Lobe history are recorded in units overlying that Peoria and Roxana Silts. Evidence from northern Illinois and southern Wisconsin suggests a substantial retreat (>100 km) after ~23.0 ka, based on sediments associated with glacial Lake Milwaukee. Additional radiocarbon ages from some of the intertonguing tills of Lake Michigan Lobe stratigraphy suggest a substantial readvance by ~18.7 ka during

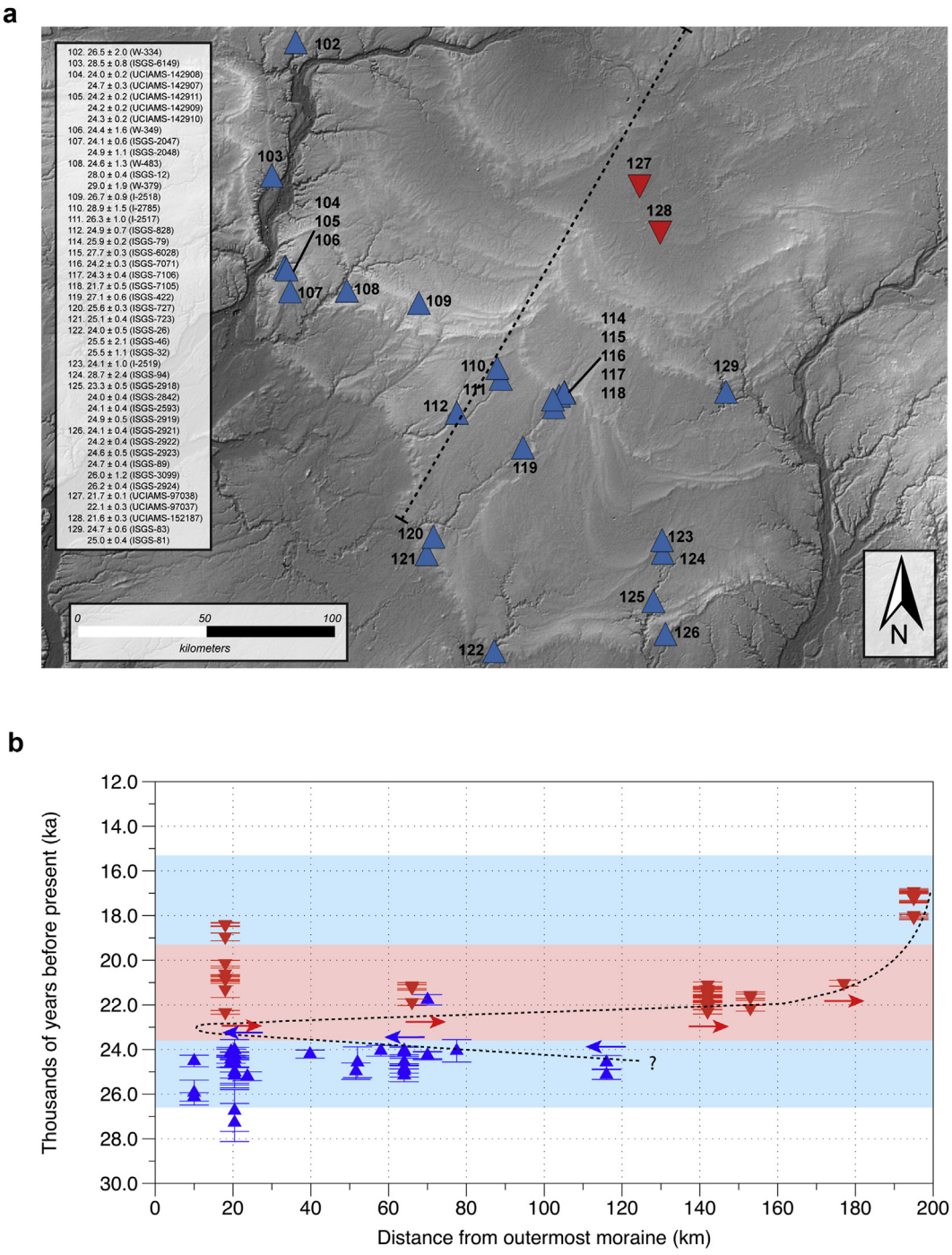


**Fig. 6. Southern Lake Michigan Lobe Chronologic Data** a) Map featuring DEM of the southern Lake Michigan Lobe in Illinois. b) Interpretation of time/distance plot with Lake Michigan Lobe ice margin position as dashed line. Symbols correspond to key in Fig. 5 and 6a. Symbols and figure format is the same as in Fig. 5.

HS1, known locally as the Crown Point Phase (Curry et al., 2018; B.B. Curry, personal communication).

Minimum ages for retreat of the Lake Michigan Lobe in Illinois come primarily from ice-walled lake plain deposits (Table S1, Figs. 6 and 7) as noted below. These former lakes formed in depressions on dead-ice permafrost (Curry, 2008; Clayton et al., 2008; Curry et al., 2010). Named DeKalb mounds after their type location in DeKalb County, Illinois, their stratigraphy commonly consists of a basal sand and gravel layer overlying till. This sequence is then overlain by organic-rich laminated lake sediment, another sand and gravel, and capped by loess. During deglaciation, as the ice stagnated and melted, these sediments were eventually let down, leading to inverted topography (Curry, 2008; Clayton et al., 2008; Curry et al., 2010). Radiocarbon ages of leaves and stems of tundra plants, such as *Dryas integrifolia* (Curry and Yansa, 2004) yield minimum ages for the formation of the lake on the dead-ice permafrost surface, and therefore the stagnation and down-wasting of the ice itself. These ages are close minimum brackets because sedimentation occurs directly in contact with the ice (Curry et al., 2010). Ages on organics from ice-walled lake plains typically are from 500 to

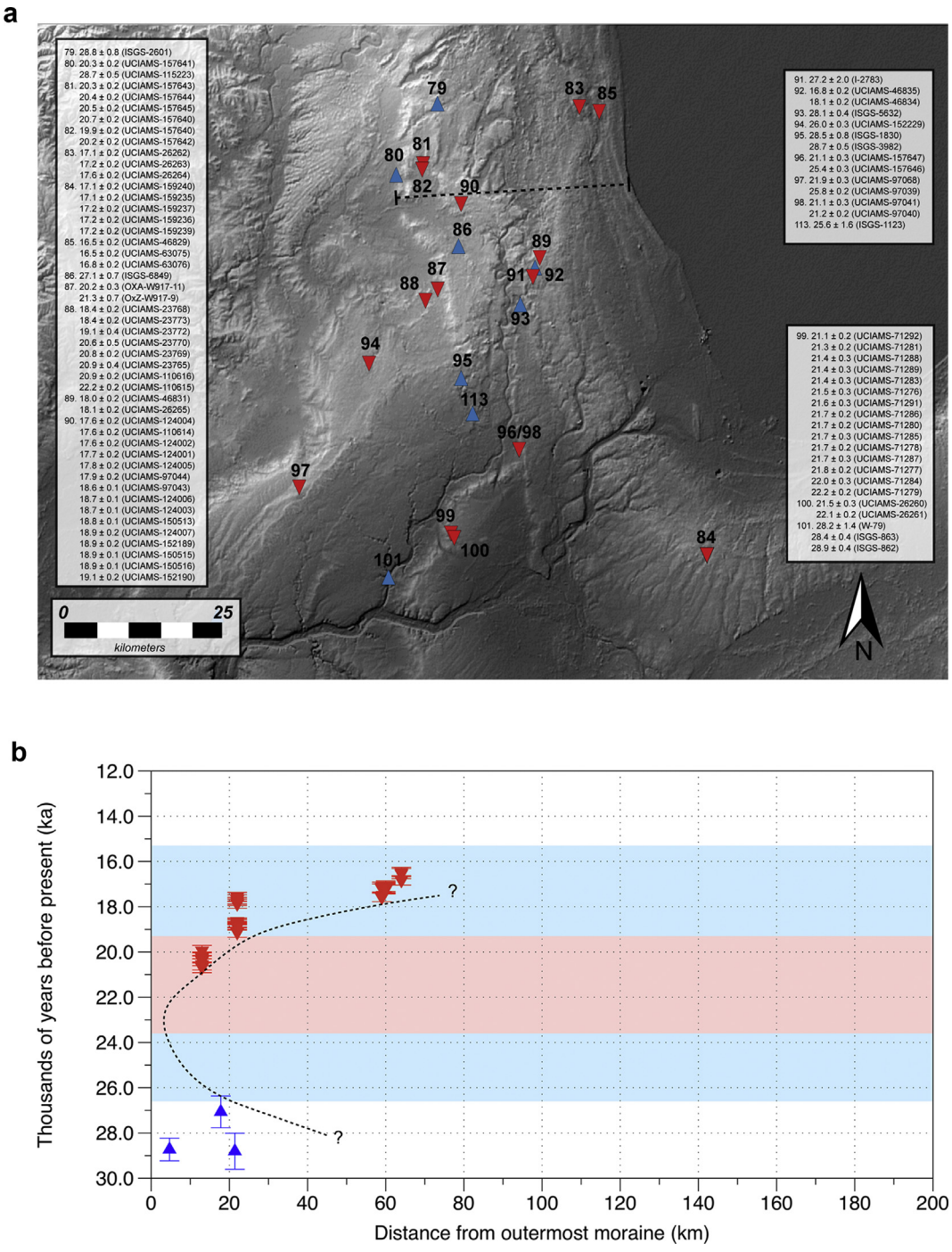


**Fig. 7.** a. **Northern Lake Michigan Lobe Chronologic Data.** Map featuring a DEM of the northern Lake Michigan Lobe in Illinois and Wisconsin. This map includes the Harvard Sublobe as well as some ages included in Fig. 6 (southern Lake Michigan Lobe time-distance). b) Time/distance plot with Harvard Sublobe ice margin position interpretation superimposed as a dotted line. Symbols and figure format are the same as Fig. 5.

5000 yrs older than ages of organics from the basal "trash zone" of kettle lake successions located on or adjacent to the same moraine (Curry et al., 2018).

We will discuss the chronologic data from IWLP sites starting at the outermost moraine belt, and progress northeastward, towards the youngest moraine belt near the present shore of Lake Michigan. The type DeKalb mounds in northern Illinois are dated by radiocarbon ages from three sites: Burlington, Hampshire and Schnucks (Sites 88, 87, and 94, respectively). The Burlington site yields eight ages, which range from 22.3 ± 0.2 to 18.4 ± 0.2 ka (Curry, 2008). The Hampshire site yields two ages of 21.3 ± 0.7 and 20.2 ± 0.3 ka (Curry, 2008), and the Schnucks site yields just one age of 26.0 ± 0.3 ka. The nearby Paw Paw Moraine has two IWLP sites that yield four radiocarbon ages that range from 25.4 ± 0.3 to 21.1 ± 0.3 ka (Sites 96 and 98). The Gilman moraine in the central LML footprint has two IWLP sites that yield three radiocarbon ages that range from 22.1 ± 0.3 to 21.6 ± 0.3 ka (Sites 127 and 128). Similarly, two IWLP sites along the Marseilles moraine complex, which lies ~50 km west of the terminal moraine (Sites 99 and 100; Curry and Petras, 2011), yield 17 radiocarbon ages that range from 22.2 ± 0.2 to 21.1 ± 0.2 ka. One site from Minooka Moraine IWLP (Site 96) yields two ages of 25.4 ± 0.3 and 21.1 ± 0.3 ka. Finally, the Valparaiso Moraine, which wraps around the southern end of Lake Michigan, yields three IWLP sites: PC, Crabtree Nature Center and South Barrington (Sites 84, 89 and 92, respectively). The PC site yields five ages that range from 17.2 ± 0.2 to 17.1 ± 0.2 ka (Bruegger, 2016). The Crabtree Nature Center site yields two ages of 18.1 ± 0.2 and 18.0 ± 0.2 ka, and the South Barrington site yields two ages of 18.1 ± 0.2 and 16.8 ± 0.2 ka (Curry, 2015). Taken together, these radiocarbon ages from IWLP record the timing of stagnation of the Lake Michigan Lobe (Figs. 6 and 7). With the exception of the ages from the outermost moraine belt (Sites 88, 87 and 94), which range from 26.0 ± 0.3 to 18.4 ± 0.2 ka, the ages tend to decrease with more distance from the outermost moraine (Fig. 6b). This suggests a steady retreat of the margin over the course of HI (23.5–19.3 ka) and HS1 (19.3–15.3 ka).

### 3.4.2. Harvard Sublobe chronology

The Harvard Sublobe moraines are discontinuous with and cross-cut the other major moraine belts of the Lake Michigan Lobe (Curry and Yansa, 2004). This flow line is significantly shorter than that of the Peoria Sublobe (Fig. 6). The sites are described from west to east. Maximum limiting radiocarbon ages for the Harvard Sublobe advance also come from the Robein Member of the Roxana Silt and the Morton Tongue of the Peoria Silt. These three ages range from 28.8 ± 0.8 to 27.1 ± 0.7 (Sites 79, 80, 86; Curry and Pavich, 1996).

Minimum radiocarbon ages associated with the west-ward flowing Harvard Sublobe come from ice-walled lake plain deposits with radiocarbon dated organic material in northeastern Illinois. These sites are discussed from west to east. Two sites from IWLPs along the Woodstock moraine IWLPs (Sites 82 and 83, Fig. 7) yield five radiocarbon ages of that range from 20.2 ± 0.2 to 17.1 ± 0.2 ka (Curry, 2015; this study). To the east, IWLP deposits on the Barlina Moraine yield sixteen radiocarbon ages from the Bryn Mawr Site (Site 90; Fig. 7), which range from 19.1 ± 0.2 to 17.6 ± 0.2 ka (Curry et al., 2018). The third site, Mill Valley, yields three ages that represent the Tinley Moraine IWLP, and range from 17.2 ± 0.2 to 17.1 ± 0.2 ka (Site 84, Curry, 2015). Finally, three ages from the Wadsworth Town Hall Site (Site 85, Curry and Petras, 2011) range from 16.8 ± 0.2 to 16.5 ± 0.2 ka. These radiocarbon ages are taken as minimum ages for the timing of retreat of the Lake Michigan Lobe.

Taken together, these minimum radiocarbon ages from the Lake Michigan Lobe suggest that by HS1, the lobe had undergone significant stagnation and retreat. It is apparent from the Harvard Sublobe transect (Fig. 7b) that ice stagnation and subsequent IWLP formation within this sector of the Lake Michigan Lobe continued through HS1.

### 3.5. Green Bay Lobe

The Green Bay Lobe was fed by ice flowing through the Lake Superior basin and western Lake Michigan basin into eastern Wisconsin, where it deposited belts of both north-south and east-west trending moraines (Fig. 8). These moraines are traced into northern Wisconsin, where they converge with east-west trending moraines that mark the outermost extent of the Chippewa lobe, discussed in the next section. An extensive intermorainic area divides the Green Bay and Lake Michigan Lobes, known locally as the "Kettle Moraine". The ages of the Green Bay Lobe moraines are dated using surface exposure ages from three locations along the outermost moraine. Colgan et al. (2002) present six $^{10}$Be exposure ages from the Waterloo site along the southern Green Bay Lobe margin (site 142). These ages range from 25.4 ± 2.3 to 19.9 ± 1.4 ka. Ullman et al. (2014) present additional $^{10}$Be exposure ages from two sites in the same region (Sites 130 and 131). The outermost site (Site 130) yields samples with exposure ages that range from 26.7 ± 1.3 to 16.2 ± 1.3 ka and produce an average age of 22.1 ± 1.4 ka. The innermost site (Site 131) yields boulder samples with exposure ages of 19.4 ± 0.9 ka and 19.3 ± 1.1 ka and a mean age of 19.4 ± 0.1 ka (Ullman et al., 2014).

Along the northern Green Bay Lobe terminal moraine, Colgan et al. (2002) reports four exposure ages from the Cactus Rock site that range from 19.9 ± 1.3 to 18.5 ± 1.7 ka (Site 143). A nearby site (Site 140) yields boulder samples with surface exposure ages that range from 27.0 ± 1.0 to 19.7 ± 0.9 ka with an average of 23.4 ± 0.8 (Ullman et al., 2014). Another site just 15 km north of this moraine yields four samples with ages that range from 19.9 ± 0.9 to 16.5 ± 0.9 ka (Site 141; Ullman et al., 2014) which produce an average age of 18.4 ± 0.8 ka.

The retreat history of the Green Bay Lobe is also constrained by both OSL and radiocarbon ages from former proglacial lake environments. The OSL ages come from two sites high in the Baraboo Hills: Feltz Basin and South Bluff Basin (Sites 133 and 134, respectively; Attig et al., 2011). The Baraboo Hills mark the outermost extent of the Green Bay Lobe in central Wisconsin. Both of these sites are ideal for capturing the retreat history of the Green Bay Lobe because they can only contain lakes when dammed by ice on all sides. Therefore, any lake sediment recovered from these two sites was deposited while the Green Bay Lobe occupied the Johnstown Moraine position around the Baraboo Hills. The OSL ages from these sites come from the top of the lake sediment package, meaning they represent a maximum timing for GBL retreat from its outermost position. The uppermost age from each site is taken as the constraining age. These ages are 20.2 ± 2.3 ka and 18.5 ± 1.7 ka (Sites 133 and 134, respectively; Attig et al., 2011) and suggest that the lobe remained at this location until after 18.5 ± 1.7 ka. Carson et al. (2012) present a similar set of OSL ages from the southern Green Bay Lobe margin, however these sites lie outside the maximum glacial limit and therefore are excluded from this analysis.

The retreat history of the Green Bay Lobe is also constrained by $^{14}$C ages of proglacial lake-bottom sediments. One such site, called Hook Lake (Site 137), is a post-glacial lake deposit within 10 km outermost moraine of the southern Green Bay Lobe. Radiocarbon ages of 19.2 ± 0.4 and 14.6 ± 0.5 ka from this lake core record also provide a minimum age constraint for the retreat of the lobe (Steventon and Kutzbach, 1985). Five additional sites that lie further inboard of the outermost moraines (10–20 km) yield nine additional minimum radiocarbon ages (Sites 132, 135, 136, 138 and 139). These ages range from 17.7 ± 0.2 to 15.0 ± 0.5 (Bender et al., 1965;

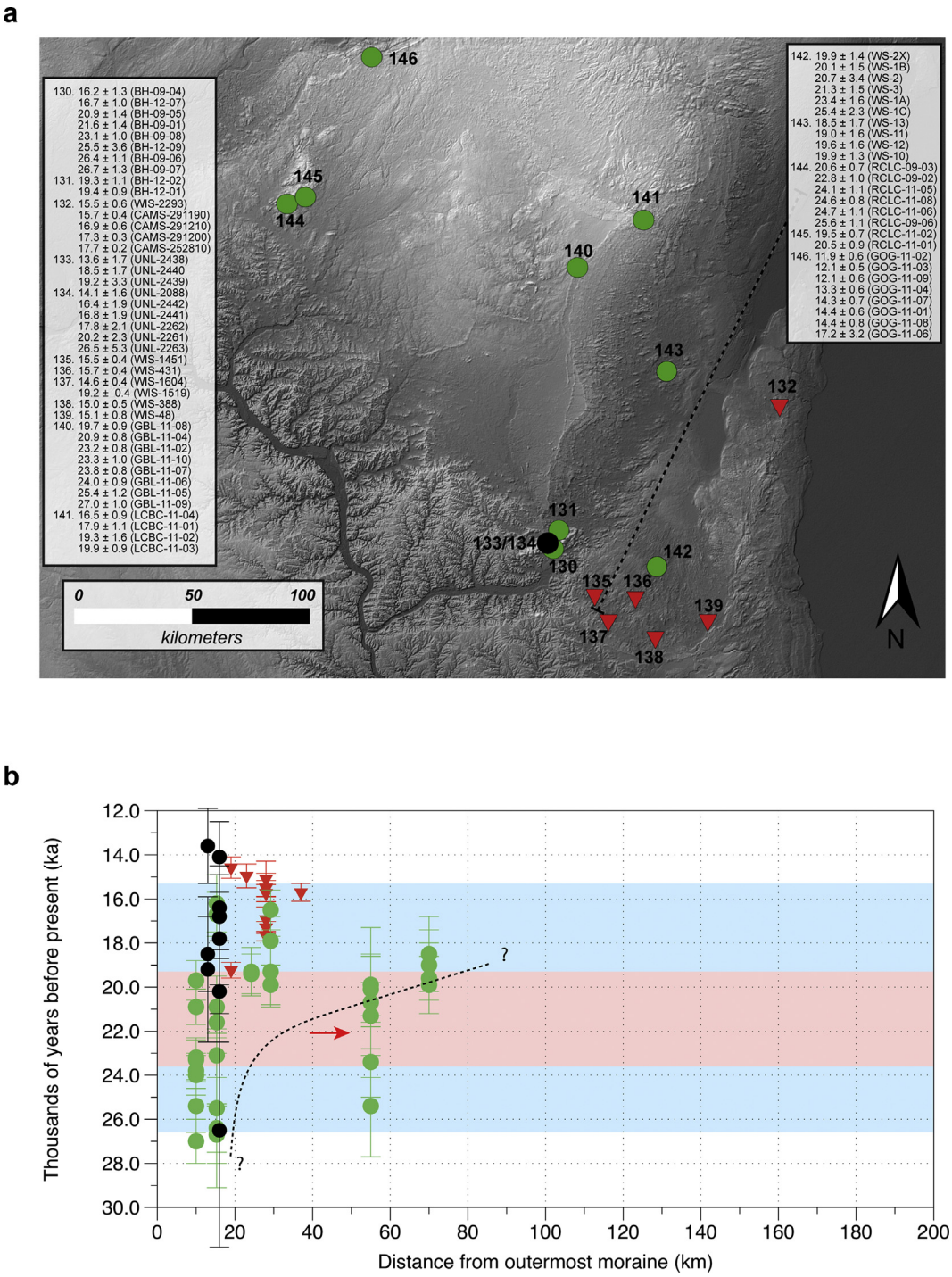


**Fig. 8. Green Bay and Chippewa Lobe Chronologic Data.** a) Map featuring DEM of Green Bay Lobe and Chippewa Lobe glacial deposits in Wisconsin. c) Time/distance plot of Green Bay Lobe with ice margin position interpretation superimposed as a dotted line. Symbols and formatting are the same as in Fig. 4 and 5. Black dots represent OSL ages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Black, 1976; Winkler et al., 1986; Maher and Mickelson, 1996; Maher et al., 1998). The Devil's Lake site in the same vicinity (Maher, 1982; Grimm et al., 2009) was excluded due to uncertain stratigraphic context – it is unclear whether that lake sediments were deposited during advance or retreat.

Taken together, the exposure age chronology of the Green Bay Lobe suggests that the ice margin underwent advance prior to ~23.4 ka, which is based on the average age of the terminal northern Green Bay Lobe moraine at site 140. Ages from sites that lie inboard of the terminal moraine (Sites 131 and 141) suggest that retreat of the Green Bay Lobe was underway by 19.2 ± 0.4 ka. The available OSL ages and minimum radiocarbon ages are in agreement with this timing of retreat initiation, suggesting that retreat started by 19.2 ± 0.4 ka.

### 3.6. Chippewa Lobe

The Chippewa Lobe flowed south through the western Lake

Superior basin and terminated in northern Wisconsin. This lobe is plotted with the nearby Green Bay Lobe in Fig. 8 to highlight their close proximity and continuous moraine systems. Ullman et al. (2014) report six $^{10}$Be exposure ages from a site along the terminal Chippewa Lobe moraine (Site 144), which range from 25.6 ± 1.1 to 20.6 ± 0.7 ka, with an average of 22.8 ± 0.9 ka (Fig. 8a). These ages represent the timing of moraine abandonment and suggest that lobe advanced to and reached its maximum position prior to ~22.8 ka, which falls during HS2 (Fig. 9). Ullman et al. (2014) also present two $^{10}$Be ages of 20.5 ± 0.9 and 19.5 ± 0.7 ka from a recessional moraine which lies about 10 km north of the terminal moraine (Site 145). This site has an average age of 20.0 ± 0.5 ka, which suggests that retreat was underway by this time.

Ullman et al. (2014) report seven ages from a recessional moraine in the Gogebic Mountains, which lie ~100 km north of the terminal moraine in northern Wisconsin (Site 146; Fig. 8a). These ages range from 14.4 ± 0.8 to 11.9 ± 0.6 ka, which produce an average age of 13.2 ± 0.4 ka. With the exception of one outlier of 17.2 ± 3.2 ka, these ages are all younger than HS1. In order for the ice margin to reach this position by this time, it requires a combined retreat of ~100 km through HI (23.5–19.3 ka) and HS1.

### 3.7. Des Moines Lobe

The Des Moines Lobe (DML) flowed southward through Minnesota and terminated in central Iowa. Several workers (Flint, 1955; Ruhe, 1969; Kemmis et al., 1981; Clayton and Moran, 1982; Bettis et al., 1996) have made significant contributions to understanding this region's glacial history. The timing of DML advance is constrained by maximum ages from a glacial till unit (Dows Formation) and the underlying alluvium (Ruhe, 1969; Kemmis et al., 1981; Hallberg and Kemmis, 1986), and minimum-limiting radiocarbon ages of organics from overlying outwash. The oldest radiocarbon ages of 24.1 ± 1.7 ka (Site 171; Ruhe, 1969) comes from a till unit known locally as the Tazewell till, which underlies the Dows Formation and alluvium. This radiocarbon age is from the outer moraine of the Des Moines Lobe and suggests an advance during HS2.

Benn and Bettis (1981), Bettis and Hoyer (1986) and Lowell et al. (1999) report radiocarbon ages on wood recovered from an alluvium unit that underlies the Dows Formation exposed at Saylorville Spillway (Site 168; Table S2). These ages range from 20.5 ± 0.4 to 15.7 ± 0.4 ka, and are maximum ages for the advance of the lobe to its southernmost extent. Ruhe (1969) and Bettis et al. (1996) report additional radiocarbon ages from below the Dows Formation at the National Gypsum site (Site 156), which range from 18.5 ± 0.4 to 16.2 ± 0.7 ka. An additional 14 ages come from a unit underlying the Dows Formation exposed at 10 sites (Sites 155, 160–167, 169) range from 20.6 ± 1.2 to 14.4 ± 1.4 ka (Ruhe, 1969; Bettis and Hoyer, 1986). These ages represent organic material in alluvium that formed prior to the expansion of the Des Moines Lobe and the associated deposition of the Dows Formation till. Finally, radiocarbon ages of organics collected from within the Dows Formation at seven additional sites also afford a maximum age for timing of Des Moines Lobe expansion. These eight ages range from 17.5 ± 0.5 to 14.8 ± 0.8 ka (Sites 149, 150, 154, 157, 158, 159; Ruhe, 1969, Kemmis et al., 1981, Bettis et al., 1996).

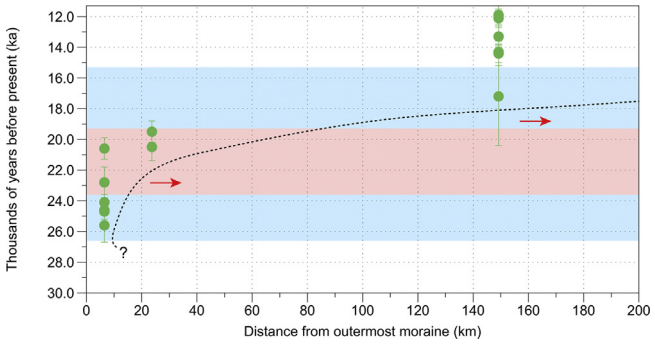


**Fig. 9. Chippewa Lobe Time/distance plot**. Time/distance plot of the chronologic from the Chippewa Lobe in Wisconsin using data presented in the map of Fig. 8a with ice margin position interpretation superimposed as a dotted line. Symbols and formatting is the same as in Fig. 4.

Minimum ages that constrain the timing of Des Moines Lobe advance come from post-glacial lake cores and radiocarbon ages of organics collected from outwash sediments. Each of these sites is discussed in order of stratigraphic position, from oldest to youngest. A radiocarbon age of 17.6 ± 0.9 ka from the McCulloch Bog Site (Site 153; Fig. 10a; Ruhe, 1969) and one age of 17.0 ± 0.4 ka from Little Millers Bay (Site 147; Bettis et al., 1996) were both collected from material that overlies the Dows Formation directly, although both are much closer in age to the maximum ages collected from within the actual till. Other minimum ages from the DML include two ages of 15.5 ± 0.8 and 15.3 ± 0.9 ka from outwash exposed at Britt (Site 151, Ruhe, 1969), an age of 16.7 ± 0.8 ka from Colo Bog (Site 170; Ruhe, 1969), and one age of 14.6 ± 0.6 ka from the Zuehl Farm pollen site (Site 152, Bettis et al., 1996). One additional sample from this outwash unit that overlies the Dows Formation exposed at Saylorville Spillway yields an age of 14.0 ± 0.2 ka (Site 168; Benn and Bettis, 1981). Finally, two radiocarbon ages of 14.0 ± 0.5 and 13.8 ± 0.3 ka come from peat that overlies this outwash unit at Whittemore (Site 148, Bettis et al., 1996).

Taken together, there is substantial overlap between the maximum and minimum ages from the Des Moines Lobe. The maximum ages range from 24.1 ± 1.7 to 14.4 ± 1.4 ka, and the minimum ages range from 17.6 ± 0.9 to 13.8 ± 0.3 ka. The oldest maximum age of 24.1 ± 1.7 ka suggests an advance during HS2. The presence of the overlying alluvium unit and associated radiocarbon ages suggests a possible retreat of up to 100 km after 24.1 ± 1.7 ka at the start of HI. This is followed by a readvance to the Des Moines Lobe's maximum position by 16.2 ± 0.3 ka, based on the youngest maximum age at Saylorville Spillway (Site 168). This advance culminated at the end of HS1 and was followed by a rapid retreat. This is an intriguing difference from the history of the rest of the LIS margin explored above. During HS1, the Des Moines Lobe underwent advance, and did not retreat until after HS1.

## 4. Summary

The ice sheet margin in the New England region reached its maximum extent (Site 1) by ~25.5 ± 0.4 ka, during the first phase of HS2. The margin remained relatively stable through the second phase of HS2, and underwent retreat starting by ~21.3 ± 0.4 ka. The Lake Huron-Erie Lobe advanced through HS2, underwent minor retreat between 25.2–25.0 ka, and then readvanced to its maximum extent. The Lake Michigan Lobe in Illinois advanced through both phases of HS2 and reached its maximum extent during the first phase of HS2 and retreat generally coincided with the end of HS2. The Green Bay Lobe advanced to its maximum position by 23.4 ± 0.8 ka. Limited radiocarbon ages from the Green Bay Lobe suggest that retreat may have been underway by the end of the second phase of HS2. Available cosmogenic surface exposure ages suggest that the Chippewa Lobe advanced through Heinrich Stadial 2 and reached its maximum position mid-stadial.

By the start of HS1 ~17.5 ka, the ice sheet margin in the New England region had retreated about 100 km from its maximum position. Retreat continued through HS1, with the exception of two minor readvances in central Massachusetts at ~17.3 and ~16.0 ka

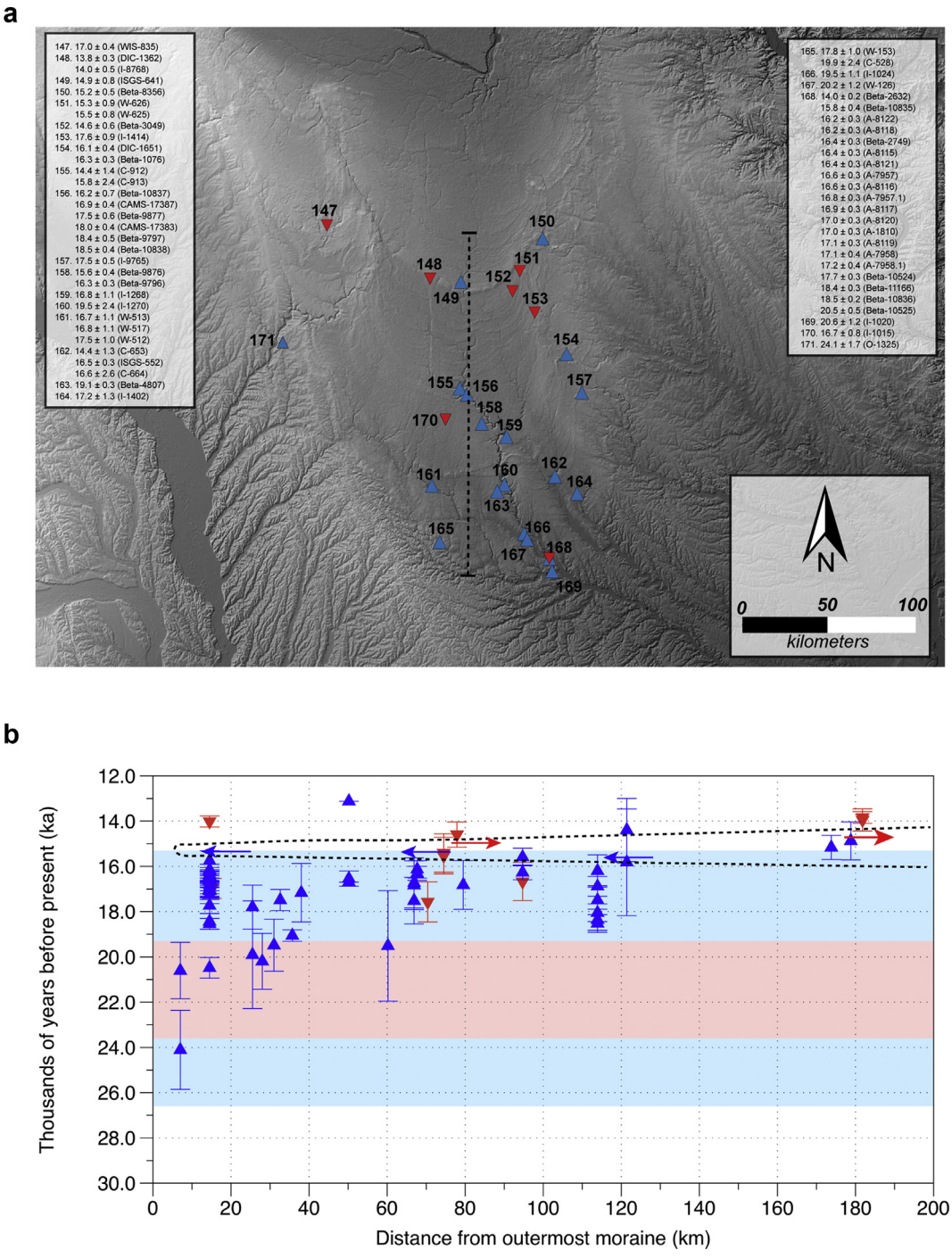


**Fig. 10. Des Moines Lobe Chronologic Data**. a) Map featuring DEM of Des Moines Lobe deposits in Iowa. b) Time/distance plot with ice margin position interpretation superimposed as a dotted line. Symbols and format are the same as in Fig. 6.

(Ridge et al., 2012), the second of which is coincident with the advance of the Des Moines Lobe. Both the Lake Huron-Erie Lobe and Lake Michigan Lobe exhibited similar behavior, having retreated nearly 150 km by that start of HS1. The Green Bay Lobe's behavior during HS1 is unclear due to the large range of ages and there is limited age control directly during the HS1 interval. The Chippewa Lobe likely retreated through HS1, based on the data available. The only lobe along the southern Laurentide margin that did not undergo retreat was the Des Moines Lobe, which advanced during HS1, reaching its maximum position ~16 ka, near the end of HS1. The lobe retreated rapidly just after this maximum.

For convenience, the behavior of each lobe is summarized in Fig. 11 as either a blue bar for advance or a red bar for retreat.

## 5. Discussion

The following sections include a discussion of the overarching patterns of LIS behavior during Heinrich Stadials. First, the original research question is revisited. Second, the behavior of the LIS is compared with that of other Northern Hemisphere ice sheet

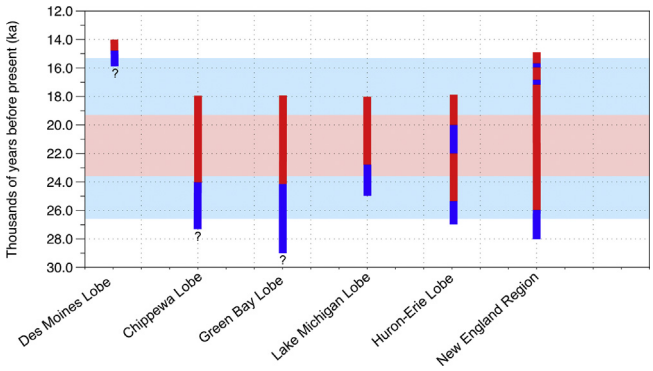


**Fig. 11. Advance and retreat history for the individual lobes of the southern LIS margin**. Summary diagram for the six lobes of the southern terrestrial margin of the Laurentide Ice Sheet. Vertical blue bars represent advance, and vertical red bars represent retreat. The horizontal blue shaded bars represent times of cold North Atlantic SST (Heinrich Stadials), and the horizontal red shaded bars represent times of warm North Atlantic SST. These patterns were derived from the discussion of chronologic data from each lobe. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

systems. Finally, a hypothesis is introduced to explain the observed differences in ice sheet behavior between HS2 and HS1 (Fig. 11), as well as the results of the Northern Hemisphere ice sheet comparison.

### *5.1. Did the terrestrial margin of the southern Laurentide Ice Sheet advance during cold phases of sea surface temperature (Heinrich Stadials 2 and 1) in the adjacent North Atlantic?*

In brief, the Laurentide Ice Sheet exhibited inconsistent behavior during Heinrich Stadials 2 and 1 in the North Atlantic. HS2 (time of cold SST) is coincident with advances of the New England region, Lake Huron-Erie Lobe, Lake Michigan Lobe, Green Bay Lobe and Chippewa Lobe. The end of HS2 is marked by the initiation of retreat for these same five lobes, and their retreat continued through the following HI. During HS1, the New England region, Huron-Erie Lobe, Lake Michigan Lobe, Green Bay Lobe and Chippewa Lobe underwent overall continued retreat. The exception being minor readvances of the New England region and Lake Michigan Lobe. In contrast, HS1 is the time of maximum extent of the Des Moines Lobe, which underwent advance only at the end of HS1, followed by very rapid retreat. Overall, HS2 is characterized by advance of the southern Laurentide margin, but following HS2, the ice sheet retreated and that retreat continued through HS1. This pattern is inconsistent with modulation of the ice sheet by SST, however it reveals a pattern of asynchronous behavior across the terrestrial LIS margin.

### *5.2. Comparison with other Northern Hemisphere ice sheets*

In this section, the glacial history of the southern Laurentide margin is compared with that of the nearby Cordilleran Ice Sheet of western Canada and the European Ice Sheets, respectively.

#### *5.2.1. Cordilleran Ice Sheet*

Radiocarbon ages from the southernmost lobe of the Cordilleran Ice Sheet (CIS) suggest a relatively late timing of maximum ice extent. The Puget Lobe of the Cordilleran Ice Sheet flowed southward, terminating in the southern Puget lowland in Washington State. The lobe reached its maximum extent during HS1, ~17.0 ka based on maximum radiocarbon ages (Porter and Swanson, 1998). Minimum radiocarbon ages from surficial outwash sediments suggest that retreat was underway by mid-HS1 time. A time distance curve reconstructed for the lobe suggests that, like the Des Moines Lobe, the Puget Lobe only remained at its maximum position for about ~100 years. This is consistent with the Des Moines Lobe record, which suggests that the lobe reached its maximum during HS1 and underwent a very rapid retreat. This implies that the same climate conditions affecting the Des Moines Lobe and causing a relatively late advance, are also affecting the southern Cordilleran Ice Sheet.

#### *5.2.2. British-Irish and Scandinavian Ice Sheets*

The British-Irish and Scandinavian Ice Sheets (BIIS and SIS, respectively; Fig. 1) are important in this discussion because of their proximity to the North Atlantic, with the possibility that they were susceptible to downstream effects associated with changes in ocean temperature. Hughes et al. (2016) summarize the timing of maximum extent for these two individual ice sheets, as well as for the entire Eurasian Ice Sheet complex. Overall, these ice sheets had all reached their maximum extent by ~21.0 ka, with some reaching their maximum extent as early as ~27.0 ka. Toucanne et al. (2015) explore the retreat history of the BIIS and SIS using mass accumulation rates (MAS) and isotopic analysis from sediment cores in the Bay of Biscay and the North Atlantic. These accumulation rates allow for the reconstruction of meltwater discharge via the Channel River over the last glacial period and termination (Toucanne et al., 2009). Toucanne et al. (2015) identify meltwater output peaks between $22.5 \pm 0.2$ and $21.3 \pm 0.2$ ka, between $20.3 \pm 0.2$ and $18.7 \pm 0.3$ ka, and between $18.2 \pm 0.2$ and $16.7 \pm 0.2$ ka. These three peaks occurred during Heinrich Interstadial and through the beginning of HS1. This suggests that the BIIS and SIS underwent retreat during the HI, which implies that the pattern of HS1-time retreat spans the North Atlantic.

The Scandinavian Ice Sheet (SIS; Fig. 1) in particular is of interest because like the Laurentide, it had a terrestrial southern margin that advanced and retreated during the last glacial period and deglaciation. Stroeven et al. (2016) provide a review of radiocarbon, surface exposure and OSL ages for the SIS and summarize the chronologic history as distinct moraine-building phases. Advance towards the southernmost margin initiated by ~25.0 ka (Ehlers et al., 2011) and the maximum extent (known locally as the Brandenburg-Lezno phase) was reached by ~22.0 ka. The ice margin then underwent a minor retreat, named the Frankfurt/Poznań phase, at ~20–19 ka. The margin retreated again, eventually stabilizing between ~18.0–17.0 ka to build moraines associated with the Pomeranian phase. Finally, the Mecklenburgian phase at ~16.0 ka marks the last period of moraine building event before the ice margin retreated into the modern Baltic Sea. Other studies (i.e. Rinterknecht et al., 2014, Marks, 2012) suggest slightly different ages for each of these phases, but they vary by at most ~1–2 ka. Overall, chronologic data from the southern SIS in Germany and Poland suggest that maximum extent was reached at the end of HS2 ~22 ka and retreated through the HI and HS1 (Houmark-Nielsen and Kjær, 2003). This overall retreat was interrupted by advances or brief stabilizations of the ice margin, allowing for moraine building throughout HS1. However, this retreat is coterminous with meltwater output into the Bay of Biscay through the first part of HS1 (Toucanne et al., 2015), which originated from both the BIIS and SIS and indicates a pattern of overall retreat through this time.

This pattern is remarkably similar to that of the eastern lobes of the Southern Laurentide. It appears that HS2 was a time of overall advance in both ice sheets, and that HS1 was a time of retreat. Not only does this suggest the possibility of similar climatic controls on the terrestrial margin of both ice sheets, but also highlights the differences between HS2 and HS1 in terms of ice sheet behavior.

### 5.3. Hypothesis for differences in Heinrich Stadials

Modeling studies (e.g. Bromwich et al., 2004) have suggested that during the Last Glacial Maximum (LGM), coincident with HS2 time, the winter Northern Hemisphere jet stream split around the Laurentide Ice Sheet, occupying a strong southerly track along the southern LIS margin, and a weaker northerly track across the Canadian Arctic (Bromwich et al., 2004). This southern track is associated with moisture advection from the Gulf of Mexico and the northern track is associated with cold air advection over the accumulation zone of the LIS (Bromwich et al., 2004). Southerly displacement of the jet stream across central North America during this time may be reflected in pluvial lake levels in the southwestern United States (Munroe and Laabs, 2013).

Changes in jet stream position and associated precipitation patterns, however, were even stronger during Heinrich Stadial 1. During HS1, the Intertropical Convergence Zone (ITCZ) in the North Atlantic shifted southwards in response to sea ice expansion (Denton et al., 2010). The effects of this shift are observed in paleoclimate records across the Northern Hemisphere. Evidence includes a weakened Asian monsoon (Wang et al., 2001), increased precipitation in the southwestern United States as recorded by speleothems (Wagner et al., 2010; Asmerom et al., 2010) and pluvial lake highstands in the western United States (McGee et al., 2012; Munroe and Laabs, 2013). These precipitation changes in this region may have been enhanced by a southward displacement of the westerlies, leading to a southwest-northeast precipitation gradient that strengthened during HS1 (Oster et al., 2015).

Based on the patterns of advance and retreat during HS1, one might also suggest an east-west trending summer temperature or precipitation gradient across north-central North America. Coupled with increased precipitation in the western United States, cooler temperatures in the west and warmer temperatures in the east would allow for such different behavior of the western and eastern sectors of the LIS margin. This is a rough approximation of direction of course, because there are very few present reconstructions of the equilibrium line altitude of the Laurentide Ice Sheet domes during the last glacial period. However, in order for there to be advance in the western sector and retreat in the eastern sector, summer temperatures were probably warmer in the east than in the west, leading to enhanced melting (retreat) in the east and reduced summer melting (advance) in the west.

This hypothesis is supported by paleoclimate records from the central United States. Pollen records (Liu et al., 2013; Jones et al., 2017) from Missouri, Kentucky and Tennessee (just south of the Lake Michigan and Huron-Erie Lobes) indicate a decline in conifer pollen and increase in oak during HI (23.5–17.5 ka) ~19 ka, indicative of warmer and wetter conditions. In order to further test this hypothesis, paleotemperature and paleoprecipitation records from near the western margin of the Laurentide Ice Sheet in Iowa and South Dakota are needed.

## 6. Conclusions

1. All but one lobe of the southern Laurentide Ice Sheet underwent advance during HS2, and retreat during HI and HS1. The Des Moines Lobe of the western Laurentide margin is the outlier, reaching its maximum extent during HS1;
2. Significant decrease in sea surface temperature does not directly affect the behavior of adjacent terrestrial ice sheet margins. However, an emergent hypothesis developed from these observations suggests that a temperature or precipitation gradient extended roughly east-west across the southern Laurentide Ice Sheet during HS1, caused by southerly suppression of the westerly wind belts over North America. In this scenario, a ridge-trough system with meridional flow (rather than zonal) could explain drastic temperature differences over North America. This is supported by paleotemperature reconstructions derived from pollen records from the mid-continent;
3. Paleoclimate records from the western United States, close to the former Laurentide margin, are necessary to determine whether either a temperature or precipitation gradient existed across central North America during Heinrich Stadials 2 and 1.

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## Appendix A. Supplementary data

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